INFORMATION SHEET ON THE APPLICATION OF DRYING-RATE NOMOGRAPHS TO THE
ESTIMATION OF TUNNEL-DEHYDRATOR DRYING CAPACITY
I. RICED WHITE POTATOES

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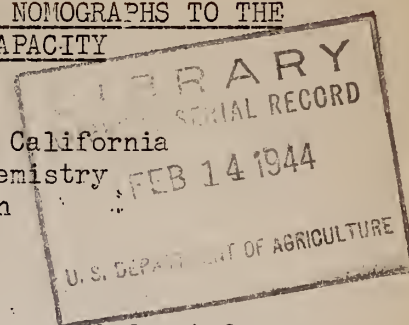
Both designers and operators of vegetable dehydrators have need for informa-
tion about the rates at which different vegetables will dry under the range
of conditions likely to be encountered in commercial dehydrators. The de-
signer must have an estimate of drying time in order to determine the length
and the heating capacity required for a drier of a given capacity. The
operator needs a rational basis for the determination of optimum tray-load-
ings and the proper degree of recirculation of air, both of which are in-
separably related to drying time. If an existing dehydrator is to be used
for some new product, an estimate of the drying time of the new product must
be made before accessory preparation and packaging equipment can be properly
designed to match in capacity.

The time required to dry prepared pieces of a vegetable in a hot-air dehy-
drator is known to depend upon at least the following factors: variety of
vegetable, method of preparation, shape and size of piece, thickness of layer,
type of tray or other support, mode of exposure to the air stream, and the
temperature, humidity, and velocity of the air stream. That is, the drying
time depends upon both the characteristics of the dehydrator and the prop-
erties of the vegetable itself.

The characteristics of a dehydrator may usually be described with reasonable
accuracy on the basis of the principles that govern the flow of air and the
properties of air and water vapor. The pertinent properties of vegetables,
on the other hand, can be determined only by experiment.

The present series of information sheets presents experimental data on the
drying times of important vegetables, correlated and summarized in the form
of nomographs in order to facilitate their practical use. This, the first
sheet in the series, outlines the general method of using drying-time nomo-
graphs and presents nomographs for the tray-drying of riced white potatoes.
An example is included.

Certain limitations on this way of estimating drying times must be noted.
Actual tunnel dehydrators fall short of the ideal conditions of air distri-
bution assumed in designs, and trays are never loaded quite uniformly with
the prepared vegetable. Most types of tunnels are substantially out of
action during the time end doors are open for the movement of trucks. In
practice, therefore, at least 20 percent should be added to the theoretical
drying time as estimated by the method presented here.

Physical Relations in a Tunnel Dehydrator

The application of heat and material balances to simple parallel-flow or counterflow tunnel dehydrators leads to the following important equations:

$$\triangle t_d = \pm\ b \triangle T \tag{1}$$

$$b = \frac{83\ M\ L_o}{G\ \Theta_f(T_o + 1)} \tag{2}$$

$$F = \frac{0.012\ M\ L_o}{\Theta_f} \tag{3}$$

$$r = \frac{a' - a_m}{a'' - a_m} \tag{4}$$

$$B = 1250\ \left[r + (1 - r)\frac{(t'_d - t_m)}{(t'_d - t''_d)} \right] \tag{5}$$

$$D = 15G\ \left[(1 - r)(t'_d - t_m) + r(t'_d - t''_d) \right] \tag{6}$$

The nomenclature is as follows:

    a - absolute humidity of air, consistent units
    b - proportionality constant (see equation 2)
    B - BTU supplied to dehydrator per pound of water evaporated
    D - heat demand, BTU per hour
    $\triangle$ - increment of, or change in, a variable
    f - mathematical symbol meaning "function of"
    F - input capacity, tons of prepared material per 24 hours
    G - mass air flow through dehydrator, pounds of air per minute
    L - tray loading density, pounds per square foot
    M - total useful tray surface in dehydrator, square feet
    r - fraction of air which is recirculated
    t - air temperature, °F.
    T - moisture content, ratio of total water to dry solids
    V - air velocity, linear feet per minute
    Θ - drying time, hours

Superscripts: ' refers to air inlet conditions
                " refers to air exhaust conditions

Subscripts: d - dry-bulb temperature
              f - final or product conditions
              m - outside or make-up air conditions
              o - initial or input material conditions
              r - reference conditions where $f(L_o) = f(V) = 1$
              w - wet-bulb temperature

These general equations are made specific by insertion of conditions imposed by the design of the dehydrator, by specifications which must be met, and by the material to be dried. Corresponding limits for the integration of equation (1), the total tray surface, and the air flow are fixed by the design of the dehydrator. The final moisture content of the material, the finishing temperature, and the tray loading density are frequently included in the specifications for the product. The initial moisture content is characteristic of the material to be dried.

Equation (1), in which the positive sign (+) pertains to a parallel-flow tunnel and the minus sign (-) to a counterflow tunnel, may be integrated by substituting suitable pairs of limits. For parallel-flow, the pairs are T_o and t'_d, or T_f and t''_d; for counterflow, T_o and t''_d, or T_f and t'_d. Upon integration, equation (1) becomes:

For parallel-flow, $t_d = t''_d + b(T - T_f) = t'_d - b(T_o - T)$ (7)

For counterflow, $t_d = t''_d + b(T_o - T) = t'_d - b(T - T_f)$ (8)

Drying Characteristics of Vegetables

The drying-rate characteristics of certain vegetables are being established by this Laboratory. Data pertaining to one of the important ones, riced white potatoes, steam-cooked for 20 minutes at atmospheric pressure, are presented nomographically in figures 1, 2, and 3. Figure 1 permits the calculation of drying times for riced potatoes under different temperature and humidity conditions for the moisture-content range from $T_o = 3.3$ to $T = 0.1$. The factors which show the effect of tray-loading density and of air velocity upon the data of figure 1 are shown in figure 3, and are related by the equation:

$$\Theta \ (at \ L_o, \ V) = \Theta_r \cdot f(L_o) \cdot f(V) \qquad\qquad (9)$$

where $f(L_o)$ and $f(V)$ correspond to L_o and V as shown in figure 3, and where Θ_r is obtained from figure 1. Figure 2 is similar to figure 1, but covers the moisture-content range from $T = 0.1$ to T_f. Note that figure 2 is independent of air velocity and tray-loading density.

Use of Equations and Figures

The continuous operation of a tunnel dehydrator requires a balance between the demands made by the physical characteristics of the dehydrator and by the drying-rate characteristics of the material to be dried. Each of the operating variables must be single-valued and these single values must be obtained by a trial and error solution. A range of conditions satisfying each demand separately may be calculated, and a combination of the two ranges establishes the possible operating condition.

Calculation of Drying Time (Material Characteristics)

Although the temperature conditions vary from point to point within a tunnel dehydrator, the drying-rate nomographs (figures 1 and 2), which are based

upon constant temperature conditions, may be applied by means of a series of approximations. The replacement of the variables T and t_d by their terminal values in equations (7) and (8) leads to:

$$t'_d - t''_d = \pm\, b(T_o - T_f) \tag{10}$$

Equation (1) states that changes in T are directly proportional to changes in t_d. Consequently, a plot of T vs. t_d for a tunnel dehydrator is a straight line whose slope is +b for parallel-flow or -b for counterflow. The ends of the straight line are located by T_o, T_f, t'_d, and t''_d. The solid line of figure 4 illustrates this point for a counterflow tunnel, $T_o = 3.30$, $T_f = 0.05$, $t'_d = 150^\circ$, $t''_d = 110^\circ$. An approximation to the straight line is shown by the dotted line which follows a series of steps. (The steps are laid out as shown, approximately one step for each 5° of difference between t'_d and t''_d. The steps should be shortest where the drying is expected to be slowest, and may be larger where the drying is more rapid.) Each full step represents a portion of the drying process as though it were occurring at a constant temperature.

The division of the drying process into constant-temperature steps permits use of figures 1 and 2. Table 1 details the steps of figure 4 and the evaluation of the drying time of riced white potatoes under the established conditions. As an example, step No. 2 occurs between T = 2.48 and 1.83, and $t_d = 120^\circ$ and 128°. The average value of t_d is 124°, and since t_w is taken as 90° (see note below table 1), $t_d - t_w = 34^\circ$ for the step. On figure 1, lines drawn from the point representing $t_d - t_w = 34^\circ$ and $t_w = 90^\circ$ to the T axis at T = 2.48 and 1.83 intersect the Θ_r axis at 0.44 and 0.90 hour, respectively. The difference in Θ_r, or 0.46 hour, is the time required for step No. 2 to occur under reference conditions. The rest of the steps are evaluated in a similar manner. The total drying time for the process is the sum of the times required for the individual steps.

If the tunnel is operated at values other than $L_o = 1.2$ lb./sq. ft. and V = 500 ft./min., the basic drying time must be modified according to equation (9). Assuming $L_o = 1.5$ and V = 900, $f(L_o) = 1.27$ and $f(V) = 0.58$ from figure 3. Under these conditions, the drying time from T_o to T = 0.1 must be multiplied by $f(L_o)$ and $f(V)$, and the drying time from T = 0.1 to T_f added to the result. Thus, if $L_o = 1.5$ and V = 900, the drying time for the assumed conditions would be $(3.57)(1.27)(0.58) + 1.20 = 3.83$ hours total drying time.

In the illustration given, a value of t''_d was assumed and the corresponding value of Θ_f was determined.* The evaluation of the counterflow tunnel requires that a range of corresponding values of Θ_f and t''_d be established which will

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*The unknown variables, depending upon the problem, may be any two of the following: T_f, t'_d, t''_d, or Θ_f. Two of these can be specified under normal conditions. The relationship between the remaining two variables can be determined by a process similar to that described in the text.

satisfy the demands imposed by the material. This range is obtained by assuming values of t''_d and determining the corresponding values of Θ_f by the method illustrated.

Calculation of Retention Time (Dehydrator Characteristics)

The demands imposed by the dehydrator may be found by combining equations (2) and (10) to obtain:

$$t'_d - t''_d = \frac{83\ M\ L_o\ (T_o - T_f)}{G\ \Theta_f\ (T_o + 1)} \tag{11}$$

The substitution of assumed values of t''_d in this equation permits the calculation of corresponding values of Θ_f, thus establishing a set of values that will satisfy the characteristics of the dehydrator.

The particular values of the variables that will satisfy the necessary conditions may be obtained by plotting a curve of drying time vs. t''_d (material characteristics) and a curve of retention time vs. t''_d (dehydrator characteristics) on the same coordinates of Θ_f vs. t''_d. The intersection of these two curves indicates the only possible values of Θ_f and t''_d under which the dehydrator will operate and still satisfy the conditions previously imposed.

With the information thus obtained, equations (3), (4), (5), and (6) may be used to estimate the capacity, amount of air recirculated, heat consumption, and heat demand of the dehydrator. The errors in calculations of the type described are considered to be less than those resulting from the uneven distribution of air flow and the uneven tray loading which occur in the design and operation of the normal dehydrator.

Table 1.--Steps in the nomographic estimation
of drying time.

Step No.	T	t_d av.	$t_d - t_w$*	Δθ$_r$	θ$_r$	θ**
	3.30				0 hr.	0 hr.
1		115° F.	25°	0.54 hr.		
	2.48				0.54	(0.40)
2		124	34	0.46		
	1.83				1.00	(0.74)
3		132	42	0.49		
	1.18				1.49	(1.10)
4		139	49	0.44		
	0.69				1.93	(1.42)
5		144	54	0.47		
	0.37				2.40	(1.77)
6		147	57	0.45		
	0.20				2.85	(2.10)
7		148.5	58.5	0.72		
	0.10				3.57	2.63
8		150	60	1.20		
	0.05				4.77	3.83

*In any non-reheating drier, the wet-bulb temperature remains substantially constant, t_w is taken as 90° F. in this example. Other values may be appropriate, depending upon local atmospheric conditions and other factors. A humidity chart is of importance in selecting a reasonable value.

**Values of θ are obtained by modifying θ$_r$ as required by equation (9), depending upon L_o and V. The values in parentheses are not required except for the investigation of conditions within the tunnel.

EXAMPLE

Given: $t_d = 130°$, $t_w = 90°$, $L_o = 1.2$, $V = 500$.
Then 0.99 hr. are req'd. for drying from
T_o to $T = 1.5$, or 2.11 hr. req'd. (3.10-0.99)
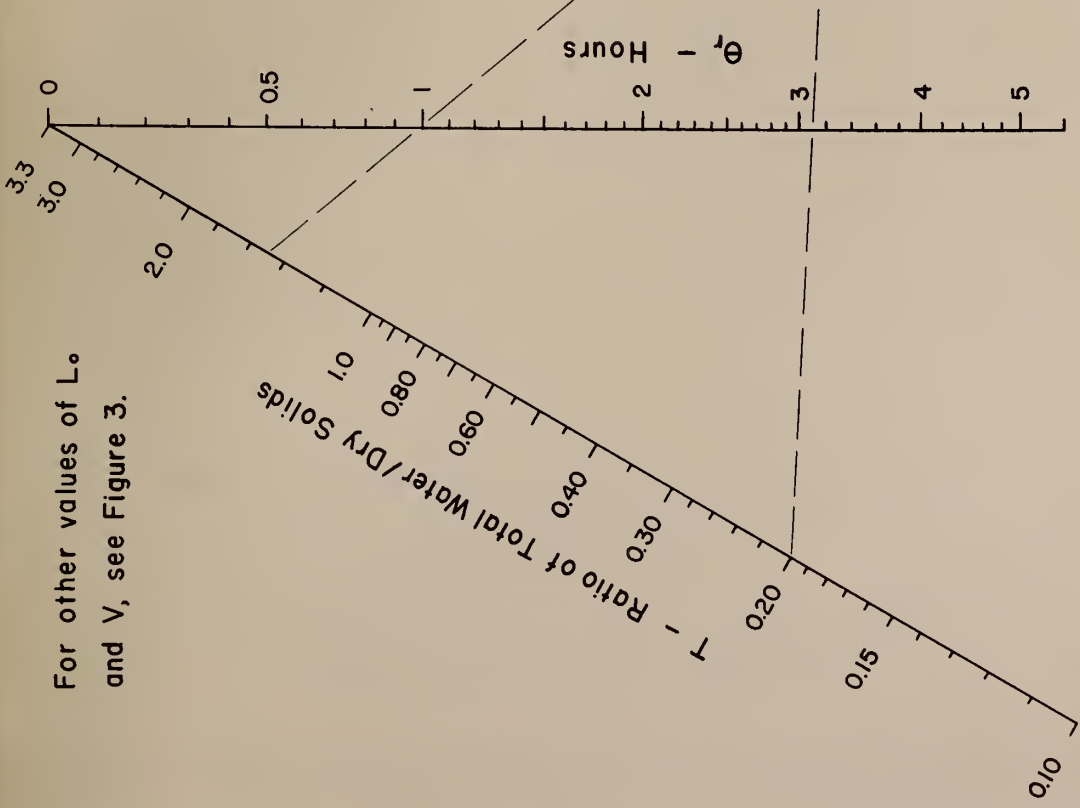for drying from $T = 1.5$ to $T = 0.2$.

For other values of L_o
and V, see Figure 3.

DRYING OF RICED POTATOES FROM T_o TO $T = 0.10$

Oregon Russet Variety   Wooden Slat Trays

$L_o = 1.2$ lb./sq.ft. $V = 500$ ft./min. Cross Air Flow

$t_d = 120°$ to $160°$ F.

FIGURE 1

EXAMPLE

Given: $t_d = 150°$, $t_w = 90°$, L_o and V within limits below. Then 1.2 hr. are req'd. for drying from T = 0.10 to 0.05, or 0.9 hr. are req'd. (2.1 - 1.2) for drying from T = 0.05 to 0.04.

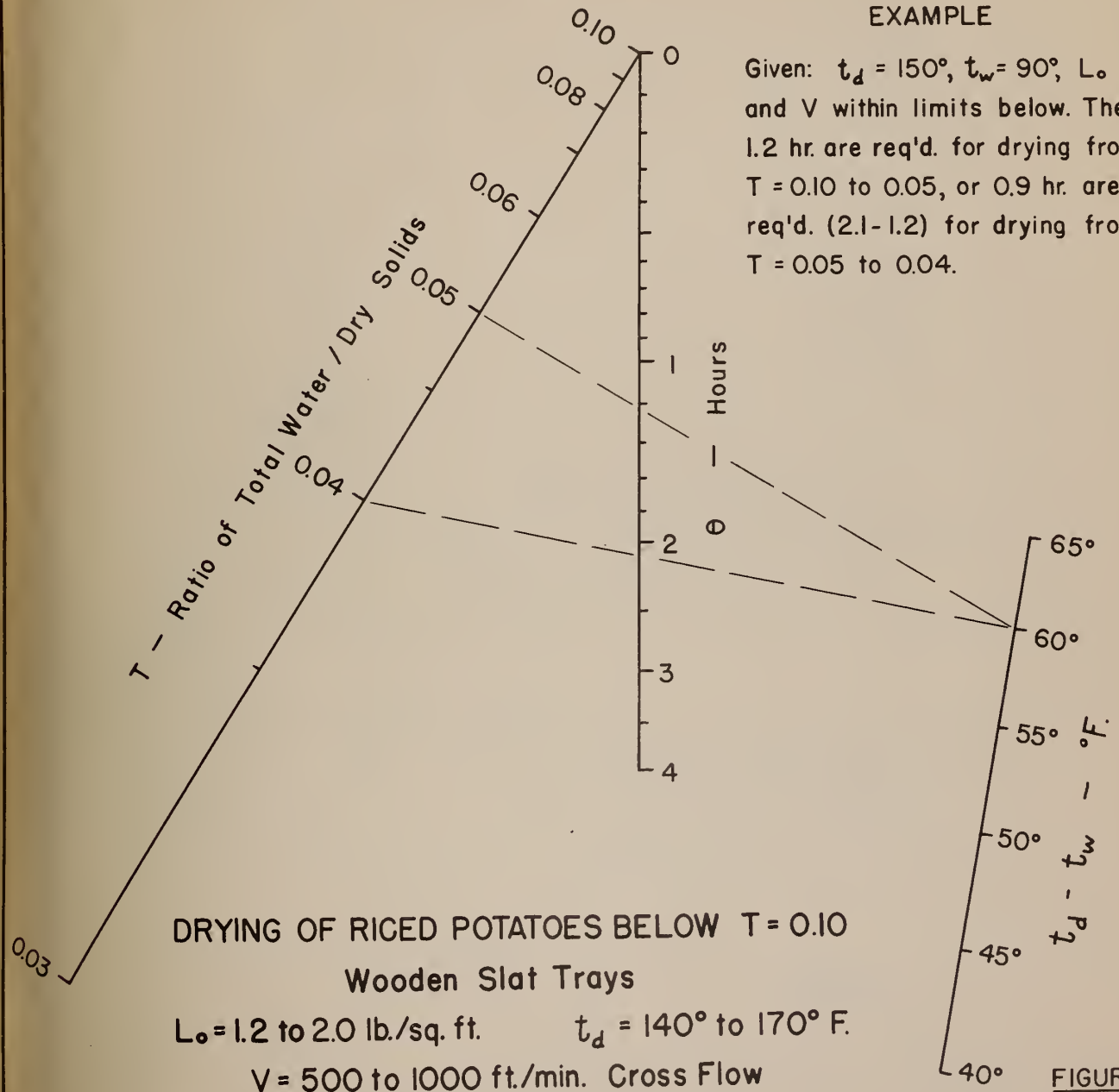T — Ratio of Total Water / Dry Solids

Hours

θ

DRYING OF RICED POTATOES BELOW T = 0.10

Wooden Slat Trays

L_o = 1.2 to 2.0 lb./sq. ft. t_d = 140° to 170° F.

V = 500 to 1000 ft./min. Cross Flow

$t_d - t_w - °F.$

FIGURE 2

FIGURE 3

RICED WHITE POTATOES
Values of $f(L_o)$ and $f(V)$ for Equation (9)
Wooden Slat Trays–Cross Air Flow

COUNTERFLOW TUNNEL DEHYDRATOR
RICED WHITE POTATOES
Moisture Content vs. Air Temperature
$t'_d = 150°$, $t''_d = 110°$, $T_o = 3.30$, $T_f = 0.05$

FIGURE 4